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UNDERGROUND CORROSION OF PIPING

By R. A. Brannon

SANITARY ENGINEERING DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

UNDERGROUND CORROSION OF PIPING

By R. A. Brannon[1]

Synopsis

Corrosion of the outside surfaces of underground metallic piping is an electrolytic phenomenon dependent on the presence at the pipe surface of water containing dissolved salts or gases. This corrosion is always associated with the flow of electric current from metal to solution and from solution to pipe. There is little difference in the rate at which metals usually employed for pipe fabricating corrode underground. It does not seem likely that metals having inherent corrosion resisting properties will be developed and made available in the quantities and at the low prices required.

The electrolytic nature of corrosion suggests two methods of corrosion control: (1) Prevention of contact between the pipe and the soil water by means of protective coating and (2) use of electric currents to counteract the currents associated with corrosion. Satisfactory and effective protective coatings are available and cathodic protection, which utilizes electric current, is being more and more widely used to control corrosion. By judicious uses of either or both of these methods almost any desired degree of corrosion control can be achieved.

The large number of variable factors that must be evaluated in each corrosion control problem gives rise to a need for engineers with specialized knowledge of the principles and techniques of corrosion control. There is a large and growing group of corrosion engineers who are acquiring more and more of this knowledge.

The success with which it is now possible to control the corrosion of underground piping may indicate a need for re-examination of earlier studies on which selection of materials for such piping was based.

Note.—Written comments are invited for publication; the last discussion should be submitted by **November 1, 1952.**

[1] Supervising Corrosion Engr., Humble Pipe Line Co., Houston, Tex.

Introduction

This discussion of the subject of underground corrosion of piping will be based on the writer's experience in the industry of transporting liquid petroleum by pipe lines, and his association with others in this industry and the related industry of transporting petroleum gas by pipe lines. Although the underground piping systems with which members of the ASCE are concerned may differ in many respects from those in the oil and gas industries, it is likely that many of the corrosion problems are common to all of them. This paper will be limited to corrosion of the outside of metal piping buried in soil.

Nature of Underground Corrosion

Corrosion of metals buried in soil results from electrolytic action between the metals and the moisture present in the soil. The moisture contains dissolved salts and gases (principally oxygen) and serves as the electrolyte in this electrolytic action. Since moisture is usually present in varying amounts, and this moisture contains varying amounts of dissolved matter, there is an infinite variety in the rate of corrosion of buried metals and in the pattern that the corrosion takes. Electrolytic corrosion is always associated with a flow of electric current. This current flows from the metal into the electrolyte (in this case the soil water) at the points at which the metal is corroding, thence through the soil water to other points on the metal surface and back into the metal. The circuit is completed by the flow of the current through the metal back to the points of discharge. The areas of metal at which current is discharged from the metal to the electrolyte are known as anodic areas, and the metal areas at which current is collected from the electrolyte are known as cathodic areas. At anodic areas, iron is oxidized from the metallic state to ferrous ions that pass into solution in the electrolyte, while at the cathodic areas a chemically-equivalent amount of ionic hydrogen is reduced to the gaseous state and plated out on the metal surfaces. There is a definite relation between the quantity of iron which goes from the metallic state into solution and the amount of current in the electrolytic circuit. One ampere passing from metallic iron into an electrolyte for a period of one year will result in 20 lb of iron being changed from the metallic to the ionic or soluble state. Conversely, the corrosion of 20 lb of metallic iron will result in the generation of the equivalent of 1 ampere-year of current.

Normally, the anodic areas are quite small in comparison with the cathodic areas. It is this characteristic of electrolytic corrosion that makes it so important to owners and operators of underground piping systems. In few cases would the metal loss resulting from corrosion be of economic importance if the loss were uniformly distributed over the entire surface area. It is this concentration of the metal loss at the small anodic areas that results in the familiar pitting of the metal. These pits frequently develop at such rates as to result in early penetration of the pipe walls.

The question, "Why do some areas of underground pipe surfaces become anodic while others become cathodic?" can only be answered by stating that the causes can be infinite in number and variety. Some of the more common causes are as follows: Variations in the concentration of dissolved salts in the

soil water; variations in the amount of oxygen dissolved in the soil water; variations in the condition of the pipe; and contact with other metals or substances such as carbon and cinders. Survey methods have been developed that may be used to predict with good accuracy the corrosiveness of soils on piping systems to be buried in them. Other methods are available for determining whether a piping system that has already been installed is corroding and where the corrosion is taking place. Consideration of these methods is beyond the scope of this paper.

The knowledge that corrosion of underground piping systems is electrolytic in nature—that is, dependent upon the presence at the metal surface of soil water, and that such corrosion is always associated with a flow of electric current, is of practical value because it suggests methods of controlling the corrosion.

Methods of Corrosion Control

Methods of Construction Other Than Burial in Soil.—Although there is a trend toward the installation of piping above the ground in the petroleum industry, the vast majority of the pipe is still installed underground. There seems to be little likelihood that the practice of burying water supply and sewage lines will be changed to any significant degree. Overhead stream crossings are fairly common in all types of piping systems and corrosion control is one of the reasons for using this method of construction. This method of control is quite important in those cases in which it is applicable but can only be used in a tiny fraction of the total amount of pipe in service. The installation of piping in conduits, with provisions for draining soil water away from the pipe, or other special construction, might be applicable in certain situations but are not usually practical for extensive piping systems.

In general, it may be stated that there is no satisfactory method of constructing extensive piping systems except by burying them underground. Exceptions to this rule are found in the case of pipe lines constructed in sparsely settled areas.

Selection of Materials of Construction.—A method of reducing the corrosion rate that naturally suggests itself to many people is that of selecting a material that is inherently resistant to corrosion. One of the principal reasons for the almost universal use of vitrified-clay pipe or concrete pipe for main sewage lines is the resistance of these materials to corrosion. The success with which certain piping materials can withstand atmospheric and other common corrosion enviroments naturally leads to the assumption that a metal can be found or produced that will satisfactorily withstand soil corrosion.

The present prospects that such a metal will be found are not encouraging. Investigations conducted by the National Bureau of Standards, Underground Corrosion Section,[2,3] have indicated that there is no significant difference in the rate of corrosion of metals commonly used in making pipe, when buried in soil. This rate applies to cast iron, wrought iron, steel (both Bessemer and open hearth), and iron or steel alloyed with small amounts of such metals as copper,

[2] "Underground Corrosion," *Circular C 450*, National Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C., 1945, pp. 241–244.

[3] "Soil Corrosion and Pipe Line Protection," by Scott Ewing, Am. Gas Assn., New York, N. Y., 1938, pp. 33–44.

nickel, and chromium. A significant reduction in the corrosion rate was observed only when the alloying elements were greatly increased, as exemplified by stainless steels such as those containing 18% chromium and 8% nickel. It is obvious, of course, that alloys such as these are not available in the quantities required for underground piping and that their cost is too high to consider them seriously for such use.

Cast-iron pipe has a long record of successful and satisfactory use under many conditions in the water supply and sewage handling fields. In so far as soil corrosion is concerned, one of the principal reasons for this success is that, being a much cheaper material on a weight basis than other metallic pipe materials, such as steel or wrought iron, the pipe is usually made with relatively thick wall sections. These thick walls allow a considerable amount of corrosion to take place before failure occurs and instances are on record in which the graphite remaining after all the iron had corroded out had continued to give satisfactory service.

Copper pipe is now being widely used in service lines from water mains to the facilities of small consumers, such as home owners and small businesses. Copper pipe has many advantages as compared with pipe made of other materials, in addition to its excellent corrosion resistance. It should be remembered, however, that copper, being a metal that is more noble than iron, will form a galvanic couple with iron and may cause corrosion of the iron in the vicinity of the contact between the two metals. Since the amount of copper pipe is usually quite small in comparison with the amount of iron pipe to which it is connected, the amount of corrosion resulting from such installations is negligible in most cases. There is a possibility, however, that an increasing use of copper pipe in conjunction with iron pipe may lead to the corrosion of the iron pipe which will be of economic importance. It should also be remembered that the copper pipe is protected from corrosion to some extent because of its connection to the iron pipe and its corrosion resistance may not be so good if it is used in sufficient quantities, or if it is electrically insulated from all buried iron structures.

The subject of selection of materials of construction as a means of corrosion control may be summarized by stating that there is no appreciable difference in the underground corrosion rate of metals commonly used in large quantities for making pipe. Pipe made of cast iron has certain advantages with regard to corrosion resistance, principally because of its structure and to some extent because of other factors such as silicon content and the nature of the corrosion products. These other factors are complicated and variable in nature and were not discussed. Piping made of higher priced material such as copper is used in limited amounts in some cases, such as for domestic service lines, in which the cost of the pipe material is not a major factor in the over-all cost of the installation.

Preventing Contact Between the Pipe and the Corrosive Agent by Protective Coatings.—Corrosion of underground piping is an electrolytic phenomenon, therefore, it is necessary that soil moisture be in contact with the surface of the pipe in order for corrosion to occur. It would seem to be a relatively simple

matter to apply a paint or coating that would keep the moisture from contact with the pipe.

Experience with iron and steel structures above ground had shown that certain paints were effective to a satisfactory degree in preventing atmospheric corrosion. When these paints were used on underground piping, it was found that the exposure conditions were vastly different. Under atmospheric conditions the painted surface would be alternately wet and dry. Even porous coatings would resist moisture for considerable periods and corrosion caused by moisture reaching the metal would stop when the surface became dry again. The soluble ferrous iron would be oxidized almost immediately to insoluble ferric oxide that would tend to plug the pores in the coating and to cover any exposed metal with dense corrosion products that were very nearly waterproof. Underground, the soil moisture was continuously present in varying concentrations so that there was little opportunity for drying of the paint film. Under many conditions, the soil water was anaerobic or free of dissolved oxygen, so the soluble ferrous iron could migrate considerable distances away from the pipe before it was oxidized. Under such conditions, protective films or coatings of corrosion products were not formed.

It soon became apparent to early operators of underground piping systems that paints that dry by evaporation of solvents are not well suited for prevention of underground corrosion in those areas where such corrosion is really severe. Evaporation of the solvent left pores in the paint film that allowed water to pass through to the metal, with the result that the pitting rate was not seriously reduced by application of the paint. These operators then turned to the application of bituminous coatings, such as asphalt and coal tar, which were heated and applied in a molten state. These coatings set to various degrees of hardness upon cooling and many of them were satisfactory in their resistance to absorption of soil moisture and maintained this property for long periods of time. These coatings usually consisted of a priming coat made up of the bitumen dissolved in a solvent. This primer, being quite thin and free flowing at the time of application, penetrated the irregularities in the pipe surface and, after drying, served as a bonding agent between the pipe and the hot bitumen.

Early destruction of many of these coatings led to the discovery that the principal cause of failure was the physical action of the soil. This action, given the name, "soil stress," results when the soil shrinks and swells with changes in moisture content and during the settling period while the loose backfill over and around the pipe is being consolidated to its normal consistency. These stresses are of considerable magnitude and are exerted over long periods of time so that the bituminous coatings, which are susceptible to cold-flow, are readily distorted and penetrated. Early attempts to overcome the effects of soil stress consisted of adding fillers to the bituminous coatings, thus increasing their resistance to cold-flow. These hardened enamels provided some improvement in coating service but it soon became apparent that additional reinforcement and shielding were required in many cases.

There are two principal requirements that a protective coating must meet. The first is that it shall be waterproof and prevent soil moisture from coming

into contact with the pipe. Owing to the obvious difficulties involved in inspecting, repairing, and recoating underground piping, this property must be maintained for long periods of time and preferably for the service life of the installation. The second is that the coating shall be able to resist soil stress to such a degree that it will not readily be penetrated to the metal at any point. It has been determined that this soil-stress action is not limited to the period of backfill settling but that it persists as long as there are changes in the moisture content of the soil that cause corresponding changes in the specific volumes of the soil.

Metal Coatings.—The use of coatings of metals more noble and more resistant to corrosion than iron, such as copper, tin, or nickel, as protection for iron pipe has not been successful because the cost of these metals limits to a few thousandths of an inch the thickness of the coating that can be applied. These thin coatings are easily broken mechanically and the underlying iron becomes anodic to the coating at the points of coating failure with the result that the pipe is rapidly pitted and early failure results. The metals that are baser than iron, such as zinc and cadmium, are more effective as coatings for pipe.

Zinc-coated, or galvanized pipe is widely used in service lines and for other installations in which small diameter pipe is necessary. The galvanized pipe gives longer service than bare iron or steel pipe because the zinc is usually attacked at a lower rate than iron, and after the zinc has corroded in some areas it continues to provide protection to the exposed iron by galvanic action. In some areas galvanized pipe does not provide satisfactory length of service and additional methods of corrosion control are needed. The life of the zinc coating is likely to be greatly reduced because of galvanic action if the small service lines are connected directly to large uncoated iron mains. The same action might result from connection of galvanized pipe to buried copper pipe. The electrical insulation from each other of pipes having different metals exposed to the soil should be considered.

Cadmium coatings, which are usually applied to iron or steel by the electroplating process, are approximately equivalent to zinc coatings in effectiveness. They are several times as expensive, however, and are not of commercial importance as pipe coatings.

Such metals as magnesium and aluminum would be suitable as coatings for iron from the standpoint of their galvanic action but they have not been used for this purpose. Advantage is being taken of their galvanic action to provide cathodic protection to iron and steel pipes.

Paints.—As a general rule, paints are not effective for corrosion protection for underground piping because most of them are not waterproof for long periods of submersion; and, because they are relatively thin, they are readily penetrated by stones, clods of earth, and soil stress. There are locations, however, in which paints such as the bitumen-in-solvent type provide economical and satisfactory corrosion control. In these cases the soil is usually sandy and does not exhibit soil-stress effects. The soil is also likely to be dry most of the time. Instances are on record in which bare pipe corroded rapidly in such soils although parallel lines painted with asphalt solution were not at-

tacked. Other factors may have also influenced the corrosion rates, but considerable benefit from the paint coating was indicated.

Pipe manufacturers realize that the rusting of pipe in transit and in storage prior to use will detract from the appearance of the pipe and sometimes result in damage. Clear lacquer or other paints are frequently applied to steel pipe to prevent this rusting. Since removal of these mill-applied paints is usually regarded as necessary before application of additional protective coatings, it is general practice to order pipe without them.

Bituminous Coatings.—The most widely used coating materials for preventing corrosion of underground piping are bituminous enamels applied in the molten state over primers prepared from corresponding materials. The enamels are nearly always reinforced by having a mat of glass fibers imbedded within them, or shielded by an outer wrap of asbestos felt, or both.

As mentioned previously, the bituminous coating materials have been modified during manufacture to increase their resistance to cold flow. There are factors that limit this modification, however, because hardness and brittleness go together and the coating must remain flexible enough at low atmospheric temperatures to permit handling of the pipe during the remaining construction operations without cracking the coating. Special enamels have been developed that remain sufficiently flexible to prevent cracking at low temperatures and that still exhibit satisfactory resistance to cold flow. These are sometimes referred to as modified or plasticized enamels.

The use of glass fibers as reinforcing materials is fairly new. Several trial uses had been made prior to 1945, but since that time their use has become quite general. When imbedded in the enamel coating, the glass fibers, possessing tremendous strength in relation to their size, act as reinforcement. This gives added resistance to shattering that might occur as the result of blows received during construction operations and to cold flow that might result from the steady, long applied forces of soil stress.

Asbestos felt, saturated with asphalt or coal tar to match the bituminous enamel, has been used as a part of pipe line coatings for many years. The felt is wrapped over the enamel, usually while the enamel is still hot, so two materials are fused together. The felt acts to extend the areas on which pressures from rocks, clods, and soil stress act, so the unit stress on the enamel is reduced and distortion is thereby reduced.

There have been attempts, with some success, to make pipe-coating shields of other materials, such as glass fibers. Rag or paper base felts were used in the beginning as pipe coating shields, but their use declined rapidly when experience showed that they were readily attacked and destroyed by soil bacteria and when the need for a long lasting shield to resist soil stress beyond the initial backfill settling period was demonstrated.

The selection of the coating structure to be used, as well as the selection of the component parts of the coating, is based on consideration of many factors, including—known or predicted severity of the corrosive action; degree of soil stress action to be expected; cost of materials and application; length of service expected of the coating; the possible use of alternate or auxiliary methods of

corrosion control such as cathodic protection; and consequences of failure of the piping system. The coating structures in which bituminous materials are utilized and some of the factors affecting their performance will now be described briefly.

Primer and enamel coatings without reinforcements or shields are not widely used because they offer little resistance to soil stress, and the additional cost of a reinforcement or shield is small compared with the total cost of the coating. The added strength of the coating is much greater than the added cost. Primer, enamel, and asbestos felt is a coating structure that is very widely used. It has adequate waterproofing and soil-stress resisting properties to give satisfactory service under a wide range of conditions. Application methods have been developed that make possible the installation of this type of coating at costs that are comparable to costs of simpler and less effective coatings.

Primer, enamel, and glass fiber reinforcement is a coating structure that came into use during a period when there was an insufficient quantity of asbestos felt on the market to meet the needs of industry. This structure is still favored by some engineers and is being rather widely used. The glass fiber material is considerably lower in cost than asbestos felt, and this probably accounts for a large part of its popularity. An outside wrap of kraft paper is frequently used with this coating structure to provide heat reflection during construction operations, greater toughness to resist damage from handling operations, and a measure of shielding effect during the period of backfill settling.

Primer, enamel, glass fiber reinforcement and asbestos felt is a fairly complex structure that may be used for one or more reasons. The value and cost of the installation may be such that the extra cost of the more effective coating may be readily justified, the pipe line may be located in an area in which its failure would be especially expensive or hazardous and extra effort should be made to prevent corrosion failures, or the soil may be unusually corrosive or exhibit unusual soil-stress effects. The use of this coating structure is quite common on major construction projects.

Mastics are coatings composed of graded sand, limestone dust, asbestos fiber, and a bituminous binder. These coatings are heated for application and are installed on primed pipe. Special equipment has been developed for application by extruding the mastic around the pipe. Upon cooling, a very hard coating is formed that has exceptionally good resistance to soil stress and moisture penetration. These coatings are usually quite thick in comparison to other coatings and experience has shown them to be very effective in preventing corrosion. The mastics have several disadvantages, such as requiring great quantities and weights of materials, leading to considerable materials-handling costs either before or after application of the coating to the pipe; specialized equipment not generally available to the industry is required for application; and special skills are required in the patching and repairing of the coating. Even considering these handicaps, it is possible under some circumstances to obtain mastic coatings at prices that are competitive with prices of other coatings.

Tapes saturated with bitumen are available for wrapping pipe. By heating the tapes during and after application fairly homogeneous coatings can be obtained. The unit costs of coatings made from these tapes are quite high, and they are intended for use at locations in which small amounts of coating are to be applied and the unit application cost of other type coatings would be extremely high.

The preparation of the metal surface of the pipe is just as important for the proper functioning of a pipe protective coating as for any paint coating. Although great improvements have been made in the equipment available for cleaning pipe, there are some conditions under which it is extremely difficult to achieve a satisfactory job of metal surface preparation. Used pipe that is rough and pitted is especially hard to clean and conditions sometimes exist in the field making complete removal of moisture from the surface of the pipe practically impossible. In cases in which the pipe is at a lower temperature than the surrounding air, there is a danger that moisture will be present on the pipe surface. Probably the best cleaning jobs are accomplished by heating the pipe to a temperature several degrees above atmospheric; sandblasting or shot blasting the pipe for removal of scale, rust, and other foreign matter; and then priming the pipe while it is still at a temperature above atmospheric.

The use of proper application techniques and proper materials—handling techniques—is especially important in the case of pipe line coatings. Once the lines are buried, inspection of the coatings to detect flaws becomes quite difficult and repair of the coatings becomes so costly as to be impractical in most cases.

Several companies specialize in the application of protective coatings to pipe in plants set up at pipe mills or at conveniently located shipping points. Semiportable plants are sometimes set up at rail heads or other points at which the pipe can be routed through the plants as it is moved to points of use. Each length of pipe is coated, leaving a few inches of bare pipe at each end for jointing. Such plants have certain advantages compared with field operations—shelter can be provided to protect the operations from the weather; it is a comparatively simple matter to provide for heating the pipe; heavier, more substantial and, in some cases, more effective equipment can be used; the pipe can be rotated for both cleaning and coating operations, permitting better inspection and control of these operations; and the ability to offer steady employment at one location may lead to more efficient work on the part of the application crews.

Equipment and methods have been developed for efficient and effective application of protective coatings in the field. The method of installation in which the coating is applied to the pipe in one continuous operation after the pipe has been joined, usually by welding, has certain advantages over the plant method of coating individual lengths of pipe and then coating the joints after the pipe has been welded into the line. Each method of coating application has advantages or objections, depending upon the conditions of the situation under which the pipe line is to be constructed. In some cases these conditions make the advantages of one or the other so obvious that selection of the method is easy. In other cases the conditions may be such as to make

the selection of method dependent upon the personal preference of the engineer or other person responsible for the selection.

Regardless of the method employed, it should always be recognized that proper application of protective coatings requires considerable skill and experience on the part of the operators and inspectors. The best of materials will be of little value if they are not properly applied.

Concrete Coatings.—Concrete coatings applied directly to steel pipe have been used to some extent. The concrete was usually applied to a thickness of 1.5 in. or more by using either removable forms or wooden forms that were left in place, or by pouring the concrete into the ditch after the pipe had been placed, with spacers to hold the pipe in position. These coatings were effective in preventing corrosion when properly applied, but have not been widely used because of the high cost and the low rate at which they can be applied.

There has been considerable use of concrete coatings over bituminous coatings for special applications. These coatings have been applied by forming in molds or by cement guns or variations. They are usually applied for the dual purpose of providing a rigid outside shield, and providing weight to prevent large diameter pipes carrying light materials (such as natural gas) from floating in marshy areas.

Grease Type Coatings.—Considerable use has been made and some is still being made of coatings formulated from petroleum greases. These relatively soft coatings sometimes exhibit remarkable resistance to soil stress. They have a tendency to absorb moisture, however, and their electrical conductance is usually high. The trend has been to incorporate harder and higher melting point materials into these coatings so that they approach the bituminous coatings in physical properties.

Plastic Tapes.—The successful use of plastic insulating tapes in the electrical field led to their development as protective coatings for pipes. Although the use of these tapes is limited, because of high material cost, to wrapping of field joints in plant or factory applied coatings and to the coating of small amounts of pipe at individual locations, there is a possibility that the convenience and low labor cost of their application will lead to their wider use. The effectiveness of the coatings has not been fully determined, but they should prove satisfactory in this respect.

Other Coatings.—Certain other coatings have been proposed and some of them have been used to some extent. Vitreous enamels have been tried and found to be effective but are subject to cracking and are high in cost. Thermosetting resin coatings are very effective when properly applied but are too high in cost for all except a few uses. No doubt other coatings have been tried and it is certain that any new coating that meets the requirement of being waterproof and able to withstand the effects of soil stress for long periods of time will receive consideration from the designers and operators of underground piping systems.

Cathodic Protection.—The second method of corrosion control suggested by the electrolytic nature of corrosion is that of controlling the electric currents that are always associated with this corrosion. Since corrosion occurs at the anodic areas at which the current leaves the pipe, it should be possible to pre-

vent current from leaving the pipe at any point and thus prevent corrosion. This can be done effectively and economically in many cases and widespread and evergrowing use is being made of the method.

Briefly, cathodic protection of underground pipe consists of connecting the negative side of a direct current source to the pipe line and the positive side to a buried structure of steel, cast iron, carbon, or graphite, called a ground bed. The electrolytic portion of the electrical circuit is from the ground bed, through the soil water to the pipe. The remainder of the circuit is through metallic conductors. The ground bed is consumed by the iron or carbon going into solution at the points at which the current enters the soil. Chemically equivalent quantities of hydrogen are plated out of the soil water onto the pipe being protected. The hydrogen plated out on the pipe tends to insulate the pipe from the soil water and to oppose the flow of additional current. The current then seeks other points of entry, so the entire pipe surface tends to collect current uniformly at all points. The local electrolytic cells are neutralized and corrosion is prevented or reduced. The effect of cathodic protection is to transfer the corrosion from the pipe where it causes damage to the ground bed where the damage can be tolerated.

While the theory of cathodic protection is simple, an endless variety of problems is encountered in the practical application of it. The amount of current required for protecting unit areas of metal, for instance, varies widely depending upon the electrical resistivity of the protective coating on the pipe, the degree to which oxidizing agents remove the hydrogen that is deposited on the pipe, and the nature of the salts dissolved in the soil water.

Protective coatings have a tremendous effect upon the amount of current required for protection. Some well-coated lines require only a few milliamperes per mile of pipe although similar uncoated or poorly coated lines may require a hundred or more amperes per mile. In some cases, complete cathodic protection of a piping system is not feasible because of the high power costs involved.

The commonly used sources of power for cathodic protection are rectifiers for converting alternating current to direct current, direct-current generators, and galvanic anodes made of magnesium, aluminum, or zinc. The galvanic anodes serve as both ground bed and power source and are used up in the process of generating power.

Since electric currents flowing in the soil always chose the paths of least resistance, they hop onto any metallic conductor going their way and ride it as far as they can. These conductors may be other pipe lines, telephone, telegraph or power cables, or any other elongated buried structure. If the current must leave the structure through an electrolytic rather than a metallic conductor to complete its circuit, the structure will likely be damaged by corrosion. This characteristic of electrolytic currents makes necessary the cooperation of all owners of underground structures within the areas influenced by cathodic protection installations. This is particularly true in urban areas in which the underground networks of pipes and cables of the various utilities are practically interlaced. Through proper cooperation, all damage can be

prevented and all participants can benefit from the application of cathodic protection.

The Corrosion Engineer

The scope of this paper, coupled with the fact that most of the points mentioned could be discussed at much greater length and the knowledge that each problem presents many variables that must be evaluated, should lead to the conclusion that specialists are needed in the field of corrosion control. There is a large group of these specialists called corrosion engineers. The field is already so broad that few individuals are expert in all phases and considerable specialization has taken place in which a particular engineer's skill is confined largely to one phase, such as cathodic protection.

Many corrosion engineers need additional training and experience. The growing awareness throughout industry of the cost of corrosion losses is leading to increasing demands for competent corrosion engineers to help control this cost. There can be no doubt that the demand will bring forth both the training and the men.

Degree of Control Attainable

For new underground piping systems it is now possible to state with confidence that, for all practical purposes, soil corrosion can be completely controlled at reasonable costs. This achievement is of tremendous importance to the industries involved and to the national economy, since it means that extra metal thickness does not have to be provided as a corrosion allowance. It may be that piping systems of interest to sanitary engineers can now be constructed of steel pipe, with its excellent properties of strength, toughness, flexibility, and ease of construction, instead of the weak, bulky, and fragile materials used in the past.

It is often possible to arrest partially or completely the corrosion of existing systems by the application of cathodic protection. Even in cases in which the power requirements for cathodic protection are high, it is usually more economical to apply cathodic protection than to replace, repair, or recoat the piping systems. The ability to keep existing systems in operation is also of tremendous economic importance to the industry involved and to the United States as a whole.

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